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XXI.

CONTRIBUTIONS FROM THE PHYSICAL LABORATORY OF THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

VIII.—AN EXPERIMENTAL PROOF OF THE LAW OF INVERSE SQUARES FOR SOUND.

By William W. Jacques.

Presented, May 10, 1876.

There is every dynamical reason for believing that the intensities of light, heat, and sound, diminish as the reciprocals of the squares of the distances from their origins.

That this is true of light and heat has been demonstrated experimentally. The case of sound, however, has only been put to the test in experiments so crude as not at all to warrant the assumption of the law on experimental grounds.

The following method (which was suggested by the reading of Professor Mayer's paper in the "American Journal" for January, 1873) ranks in its degree of accuracy with those which have been applied to the verification of this law in the cases of light and heat. It depends, primarily, on the principle, that, when a particle of air is solicited by two equal and opposite forces, it will remain at rest.

If two resonators, adjusted so as to resound with equal intensity, be placed equally distant from an organ-pipe, and connected by tubes with the two prongs of a fork-shaped tube in such a way that the sound-wave from one resonator shall arrive at the fork in opposite phase to that from the other, we shall have this condition; and, if the stem of the fork be placed in the ear, no sound will be heard. If, in place of one of these resonators, we put two, each of the same intensity as the first, both connected with the same prong of the fork, we may, by moving them farther from the source of sound than was the single resonator, at the same time altering the length of the tubing so that the wave from the single one shall arrive at the fork in opposite phase to that from the pair, produce the same effect of complete interference. If the law of inverse squares holds true, the distances of the single resonator from the source of sound should be to the corresponding distance of the pair as $1:\sqrt{2}$. If three resonators be opposed to one, the distances should be $1:\sqrt{3}$; if four resonators, $1:\sqrt{4}$ or $1:2$, &c.

It will be seen that the accuracy of the above method depends upon the following conditions: —

1st, That the resultant wave from the combination of two resonators has twice the intensity of that coming from one.

2d, That the decrease in intensity of a sound, in passing through a tube, is inconsiderable.

3d, That the intensity of resonance is proportional to the intensity of vibration at the mouth of the resonator.

Let us first see the arrangement of the apparatus used, and then determine how nearly these three conditions are satisfied.

As a source of sound, a C_3 closed organ-pipe was used, blown by a stream of air from a large gas-holder having an arrangement for keeping the pressure constant. The pipe was mounted on a small standard, raised some four feet above the floor, so that the sound-waves produced might have opportunity to diverge equally in all directions. At a measured distance from the embouchure of the pipe were placed two resonators, each cylindrical in shape, and capped with a hemisphere at one end, through which ran a tube ¼-in. in internal diameter, and at the other end with a flat plate, in which was a circular aperture of 1.5-inch diameter. The resonators were telescoped, so as to be readily adjusted for pitch and intensity. From the small tubes of the pair of resonators pieces of rubber tubing led to the two prongs of a forked brass tube, in which the waves from the two resonators came together, and augmented each other. From the stem of the fork another tube led to one arm of the trombone interference apparatus of Herschel. The third resonator was placed at an appropriate distance from the embouchure of the pipe, and so arranged that it could be moved to or from the pipe, and, at the same time, one arm of the interference apparatus could be moved to compensate for the change in phase due to such motion. From the small opening of this resonator a rubber tube extended to the other arm of the interference apparatus; and in this tube was inserted a brass fork precisely like that used for the pair of resonators, excepting that one of its arms was stopped, so that the conditions of reflection for this wave might be as similar as possible to those from the pair of resonators. If all these conditions of reflection be the same, it follows that two resonators give twice as great an intensity as one placed at the same distance from the source of sound.

The second condition, that the decrease in intensity in passing through a tube is inconsiderable, is abundantly proved by the experiments of Biot and Regnault in water-pipes. The third condition, that the intensity of resonance varies directly with the intensity of vibration of the air just outside of the resonator, seems not to be susceptible of experimental proof, excepting on the assumption of the law of inverse squares.

There seems, however, to be no cause for any considerable variation from this ratio: and if, upon trial, we find that the law does hold, it is reasonable for us to conclude that the variation of resonance is proportional to the intensity; for it is extremely improbable that there would be two errors which would exactly counterbalance each other.

The resonators having been adjusted so as to resound with equal intensity by comparing them two at a time on the interference apparatus, it was only necessary to connect three resonators as described above, so that the resultant wave should act on the air contained in the tube which enters the ear. Keeping now the pair of resonators in a constant position, and moving the single resonator and one arm of the interference apparatus until the resultant sound is at its minimum intensity, the relative distances should be $\sqrt{2}:1$.

Below are given several series of readings of the distance of the single resonator from the source of sound. The first three columns are the results of experiments made in front of the pipe, the pair of resonators being placed at a distance of 142 cms. from the embouchure. The resonators were lettered, for convenience, A, B, and C; and the three series of readings are the results of opposing successively A to B and C, B to A and C, and C to A and B. In the last three columns are given the results of similar measurements behind the pipe, the embouchure being still taken as the source of sound, and the pair of resonators being distant 177.5 cms.

At the bottom of the table the means are compared with the calculated positions of the single resonator.

The mean of the means of the first three columns is 100.3 cm; which differs from the theoretical by only 0.3 cm. The mean of the last three is 128.2, giving a difference from theory of 3.2 cm.

An inspection of the following table shows us, that, assuming the embouchure of the pipe as the source of sound, in front of the pipe the law of inverse squares holds almost exactly true: behind the pipe there is a slight difference. Theoretical considerations of the way in which the sound-waves are given off from a closed pipe would lead us to expect an error of this kind. The error due to the experiments being conducted in a hall was probably inconsiderable, as the hall was 92 feet long and 65 feet wide; and, moreover, the windows were partially open. It should be remarked, that bringing the resonators too near the pipe introduced an error of a nature and magnitude which indicated that for a sound of considerable intensity the resonance was not proportional to the intensity of sound at the mouth of the resonator; but this exception only serves to prove the rule for the case of moderate intensity.

A opp. to B & C.	B opp. to A & C.	C opp. to A & B.	A opp. to B & C.	B opp. to A & C.	C opp. to A & B.
cm.	cm.	cm.	cm.	cm.	cm.
99	102	100	128	128	128
100	100	99	129	127	131
100	100	103	129	128	133
101	100	99	129	128	131
99	102	101	125	127	132
99	99	99	127	129	127
100	100	104	125	129	128
101	103	100	127	129	129
100	104	100	126	129	126
98	103	100	129	128	126
101	100	101	128	129	127
99	100	100	128	127	127
99	101	100	128	129	128
100	101	99	128	128	129
98	100	101	128	126	124
100	102	100	132	124	129
Mean = 99.6	Mean = 101.0	Mean = 100.4	Mean = 128.4	Mean = 128.5	Mean = 127.8
Theor. = 100.0	Theor. = 100.0	Theor. = 100.0	Theor. = 125.0	Theor. = 125.0	Theor. = 125.0

It is true that these experiments do not furnish an *exact* proof of the law of inverse squares for sound; but we have not an *exact* proof of the same law in the cases of light and heat. All that we can say of any of them, on experimental grounds, is, that they are *very* approximately true.

The above experiments show that we may make this assertion for sound on as valid experimental grounds as for light or heat.